Large-scale cosmic-ray anisotropy studies at the Pierre Auger Observatory at EeV energies

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PIERRE AUGER OBSERVATORY

presented by Diego Harari

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Summary of recent results on the search for a dipole pattern in the distribution of arrival directions of UHECRs

TAUP 2013

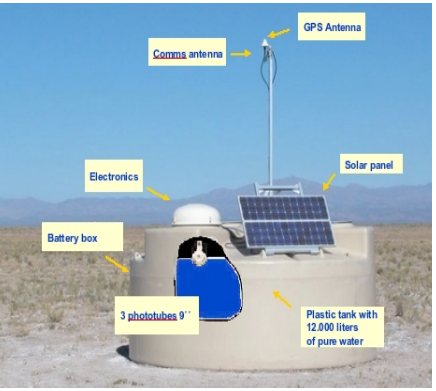
Asilomar, California, USA – September 9, 2013

Pierre Auger Observatory

Malargüe, Argentina

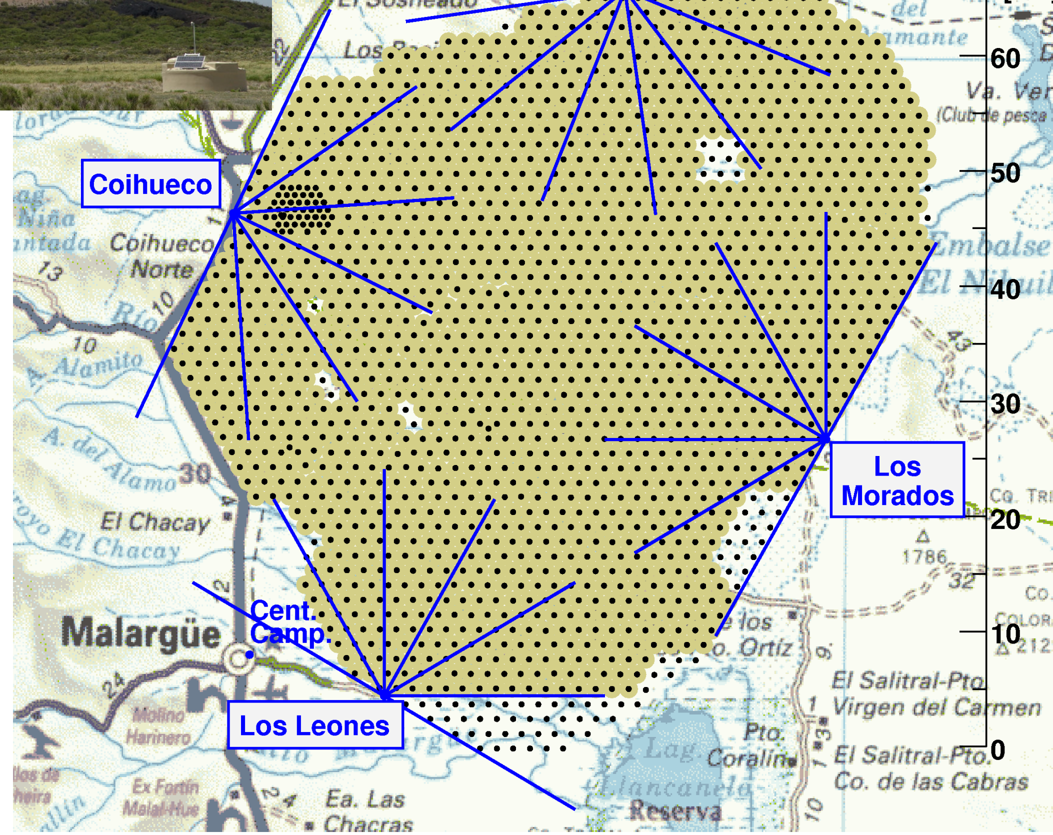
Surface Detector

1660 water-Cherenkov stations



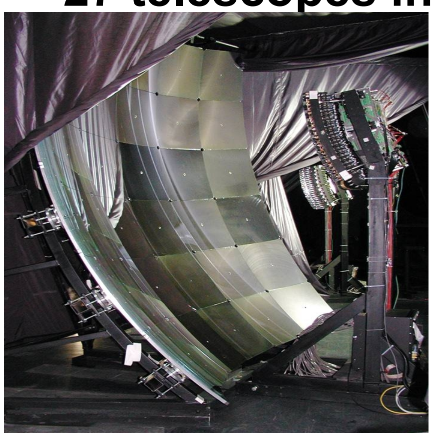
3,000 km²
1,5 km grid

25 km²
750 m grid
AMIGA: muon detectors



Fluorescence Detector

27 telescopes in 4 locations



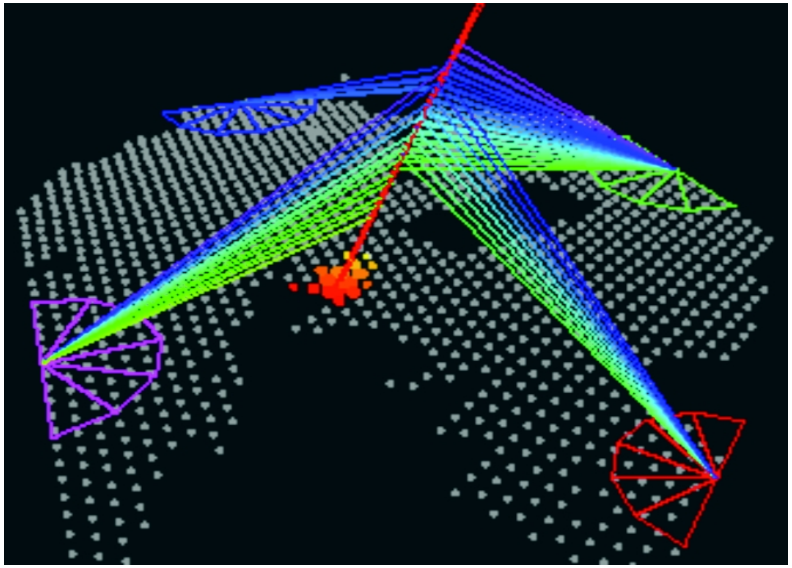
HEAT:
3 higher elevation telescopes

AERA: radio detection of EAS
AMBER, EASIER, MIDAS: GHz detection

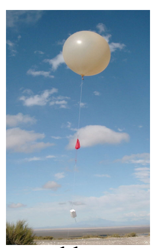
Argentina Australia Brazil Croatia Czech Republic
France Germany Italy Mexico Netherlands Poland
Portugal Slovenia Spain United Kingdom USA
Bolivia* Romania* Vietnam* (*Associated)

PIERRE AUGER OBSERVATORY

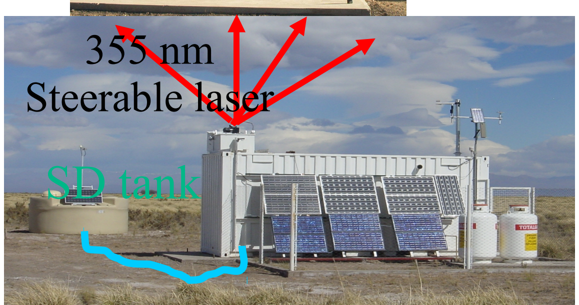
HYBRID OPERATION



Extensive atmospheric monitoring and calibration



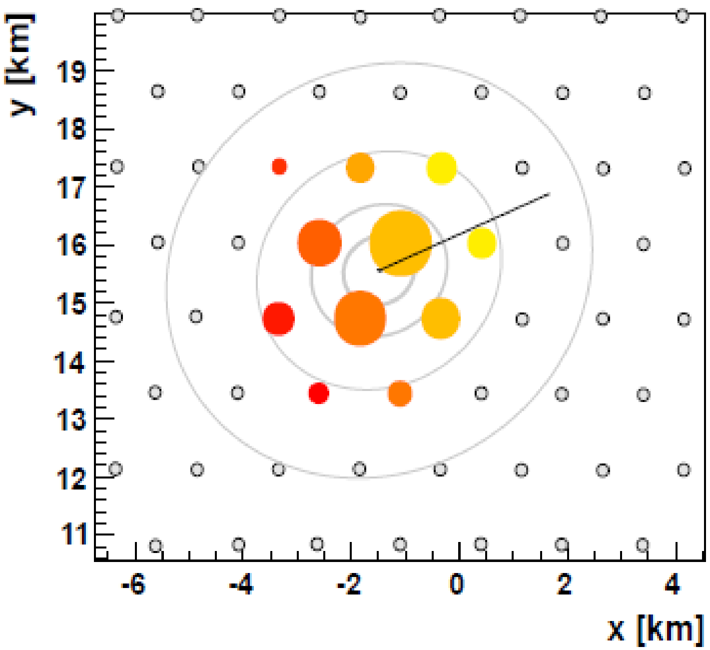
Ballons

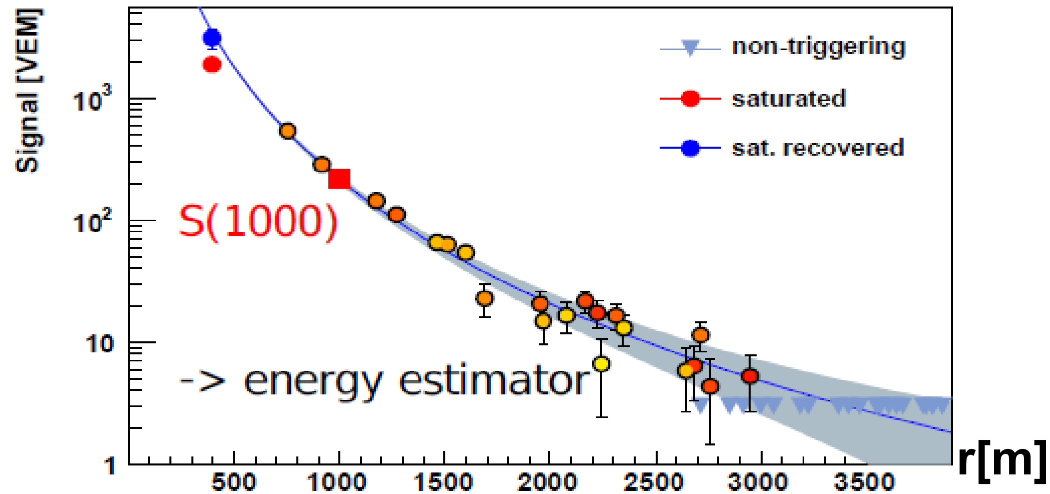


Surface detectors (SD)
"statistical power" ~ 100% duty cycle
Fluorescence detectors (FD)
Complementary view ~ 13% duty cycle

Hybrid operation:
improves precision of energy/angular calibration, consistency tests, etc.

SD Air Shower Reconstruction





Arrival directions:
From fit to arrival times of shower front

Angular Resolution

< 1° if E > 10 EeV

< 2.2° for events with low SD-mutiplicity

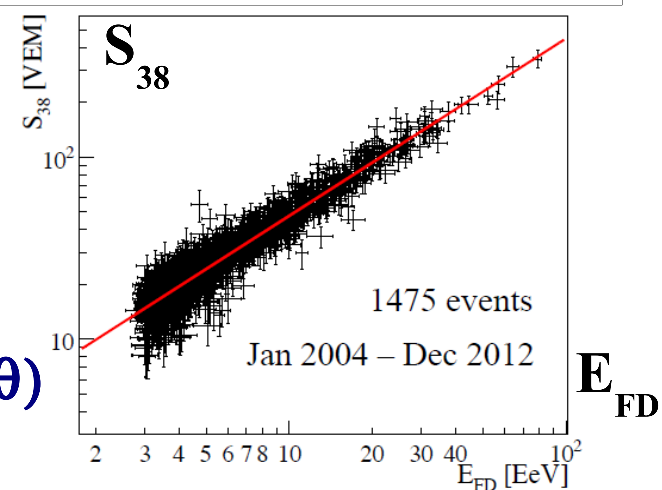
Energy Calibration

SD calibrated with FD

FD (calorimetric) energy largely independent on composition and hadronic models

Atmospheric attenuation derived from data (constant intensity method)

S_{38}=S(1000)/CIC(θ)



SEARCH FOR LARGE-SCALE ANISOTROPIES
MOTIVATION

Large-scale structure in the distribution of arrival directions
may help understand nature and origin of UHECRs

Could signal galactic-extragalactic transition

Escape of galactic CRs at EeV energies might generate dipole pattern.
Amplitude model-dependent, may be few %.

Excess along a plane could manifest as a quadrupole pattern
(e.g. galactic disk at EeV energies, supergalactic plane at highest energies)

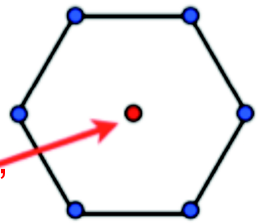
Extragalactic isotropic CRs may generate small dipole due to our motion
(Compton-Getting effect, observed at lower energies, expected below 1%)

Dipole in the Inhomogenous nearby galaxy distribution may manifest
also below trans-GZK energies

SUBTLE DETECTOR EFFECTS MUST BE UNDER CONTROL FOR %-LEVEL DIPOLE SEARCHES

$$\omega(t,\theta,\phi,S_{38^\circ}) = n_{\text{cell}}(t) \times a_{\text{cell}}\cos\theta \times \epsilon(S_{38^\circ},\theta,\phi)$$

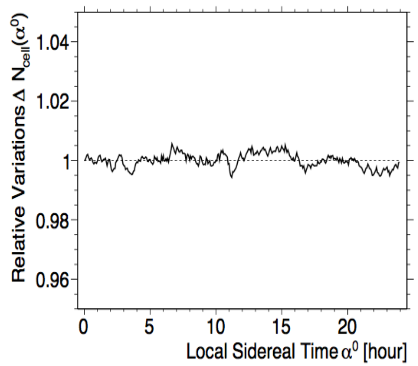
elemental cell



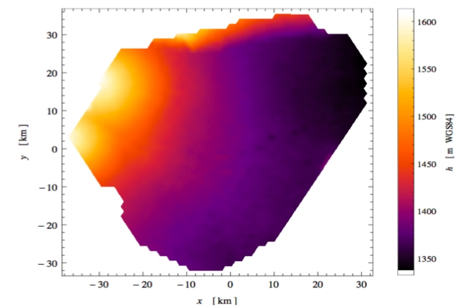
"hottest" station

Exposure modulations

Time-dependent array size

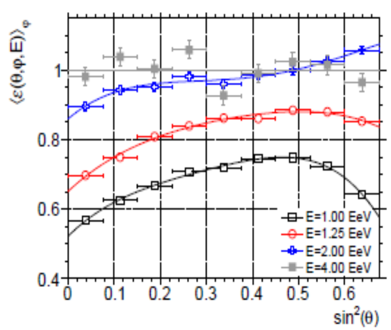


Tilt of the array

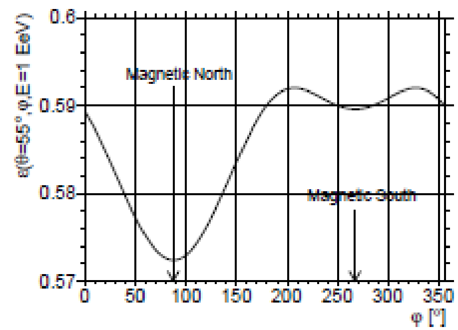


Detection efficiency

Zenith-dependence



Geomagnetic effects



Atmospheric and geomagnetic effects on energy assignment

$$S_{atm}(1000) = [1 - \alpha_P(\theta)(P-P_0) - \alpha_\rho(\theta)(\rho_d-\rho_0) - \beta_\rho(\theta)(\rho-\rho_d)]\, S(1000)$$

$$S_{geom}(1000) = \left[1 - g_1 \cos^{-g_2}(\theta)\sin^2(\widehat{\mathbf{u},\mathbf{b}})\right] S(1000)$$

TWO METHODS

1) First harmonic analysis in right ascension α

benefits from almost uniform exposure in right-ascension

E > 1 EeV: Rayleigh

$$I(\alpha) = I_0(1 + r\cos(\alpha - \varphi) + \cdots).$$

Standard Fourier analysis weighted by exposure

$$r = \sqrt{a^2 + b^2}, \quad \varphi = \arctan\frac{b}{a}$$

$$a = \frac{2}{\mathcal{N}}\sum_{i=1}^{N} w_i \cos(\alpha_i), \quad b = \frac{2}{\mathcal{N}}\sum_{i=1}^{N} w_i \sin(\alpha_i) \qquad w_i \equiv [\Delta N_{\mathrm{cell}}(\alpha_i^0)]^{-1}$$

E < 1 EeV: East – West

$$I_E(\alpha^0) - I_W(\alpha^0) = -\frac{N}{2\pi}\frac{2\langle\sin\theta\rangle}{\pi\langle\cos\delta\rangle} r\sin(\alpha^0 - \varphi)$$

Removes direction-independent systematics (but reduced sensitivity)

2) Dipole (and quadrupole) patterns

as a function of both Right Ascension AND declination

E > 1 EeV

$$\Phi(\alpha,\delta) = \frac{\Phi_0}{4\pi}\left(1 + d\,\hat{d}\cdot\hat{n}\right)$$

$$r = \left|\frac{\langle\cos\delta\rangle d_\perp}{1 + \langle\sin\delta\rangle d_{||}}\right|$$

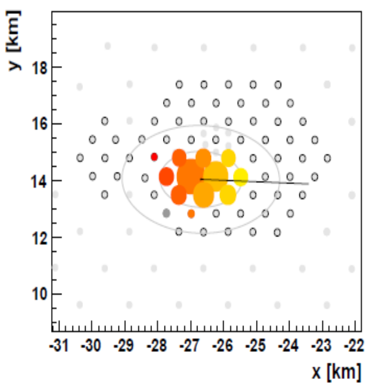
r depends on the latitude of the Observatory and range observed

First-Harmonic analysis in Right Ascension

SD Data: 1 January 2004 – 31 December 2012

E >0.01 EeV

SD 750 m, $\theta < 55°$

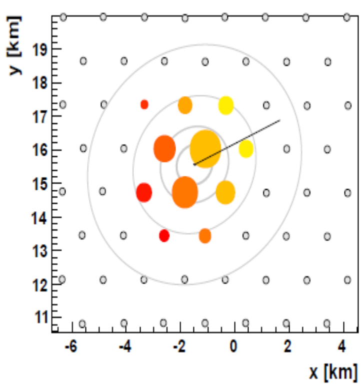


750 m events

fully efficient:
$E \geq 0.3$ EeV

energy estimator:
S_{35}

SD 1500 m, $\theta < 60°$



Vertical events

fully efficient:
$E \geq 3$ EeV

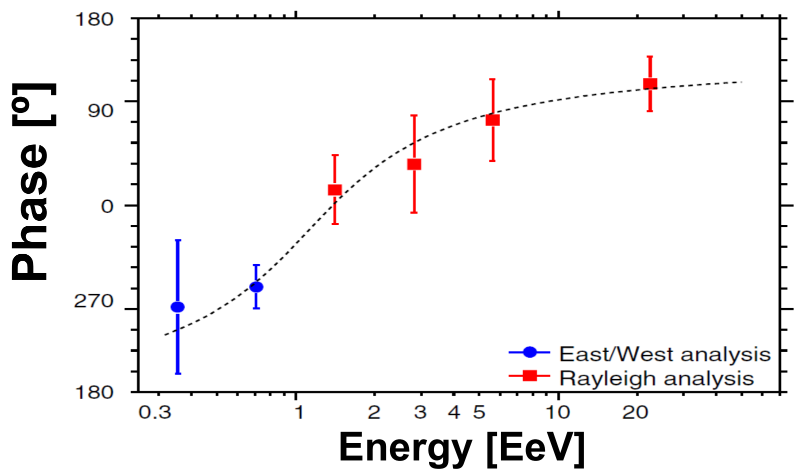
energy estimator:
S_{38}

	ΔE[EeV]	N
Infill East-West Method	0.01 - 0.025	11819
	0.025 - 0.1	428028
	0.1 - 0.25	223342
East-West Method	0.25 - 0.5	720224
	0.5 - 1	1081810
Modified Rayleigh	1 - 2	557829
	2 - 4	148790
	4 - 8	31270
	> 8	12292

3.2×10^6 arrival directions

First-Harmonic analysis in Right Ascension
DIPOLE PHASE

Astropart. Phys. (2011)

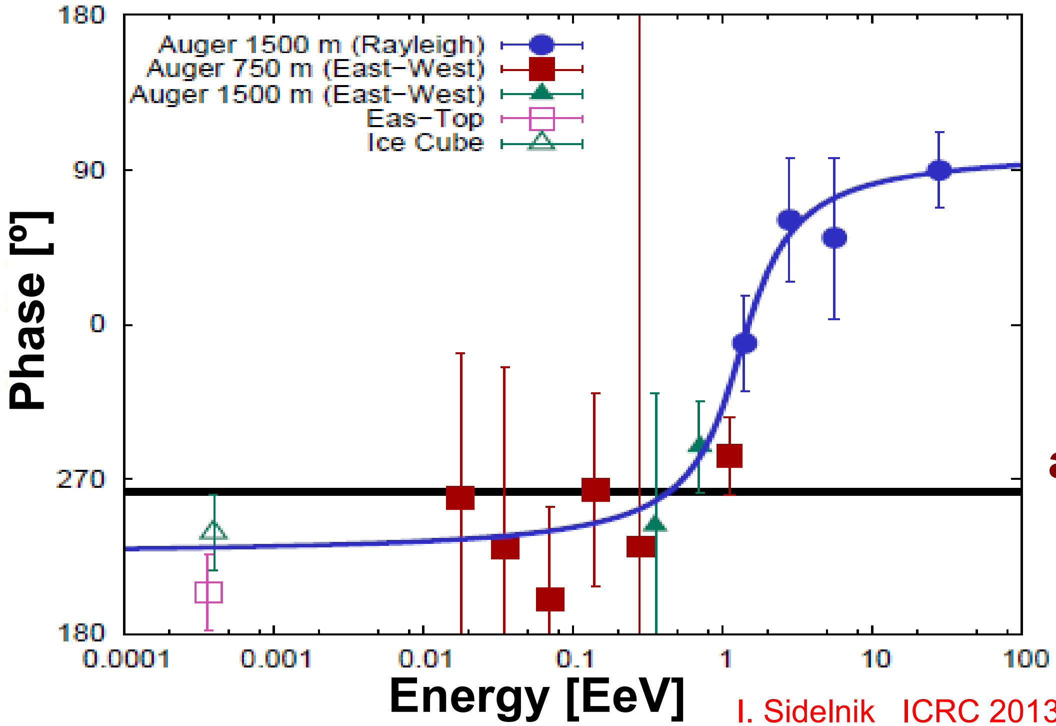


Data until Dec. 2009 E > 0.25 EeV

Hint to a constant value (RA ~ 270º) below 1 EeV

and a transition to a constant value (RA ~ 90º) above 4 EeV

Ongoing test with independent data
fit to a constant phase ~ 263º below 2 EeV
and/or fit of transition



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With data until Dec. 2012

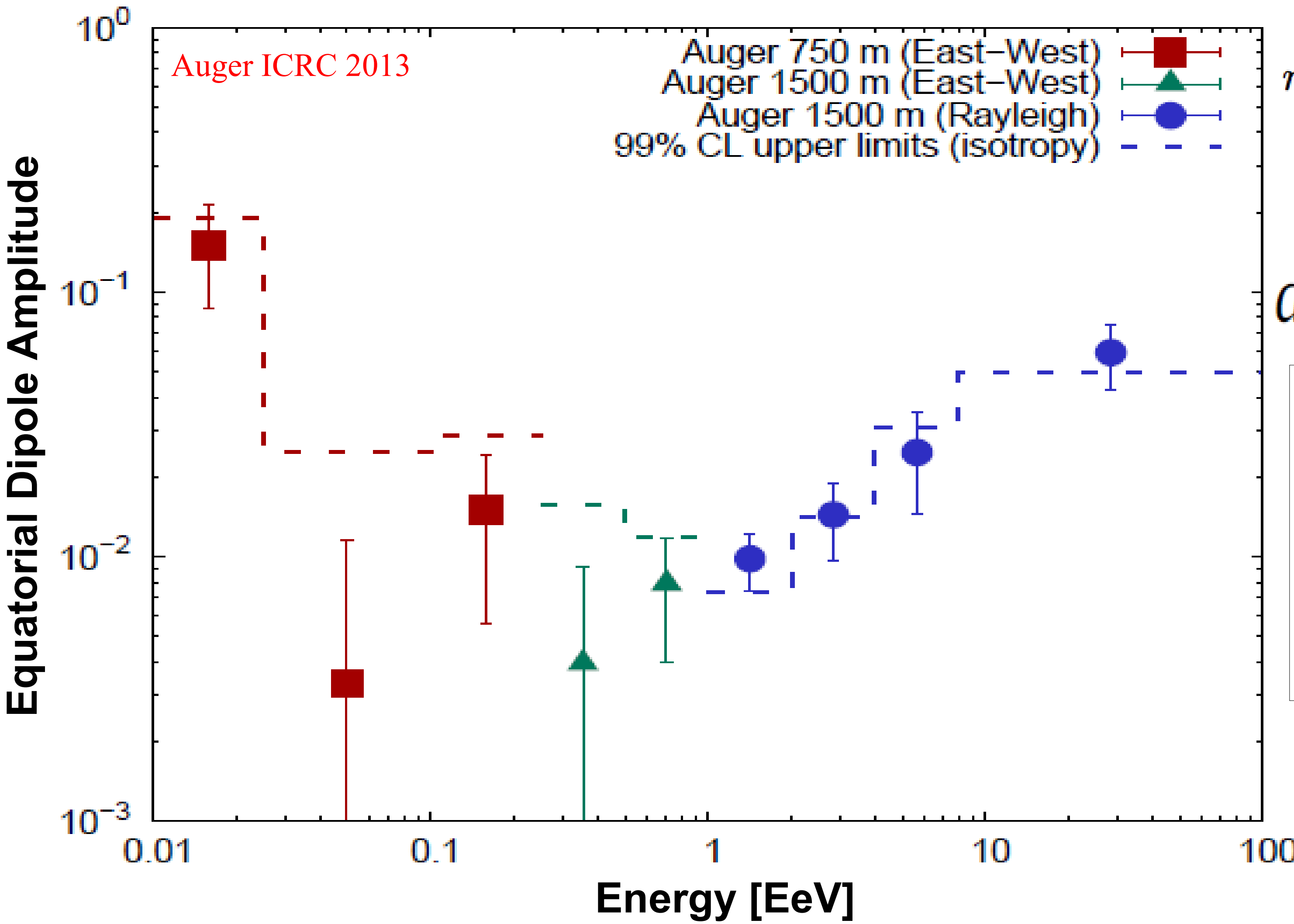
and extension to lower energies (750 m array)

Note:

Galactic center is at RA=268.4º

First-Harmonic analysis in Right Ascension

EQUATORIAL DIPOLE AMPLITUDE



$$r = \left| \frac{\langle \cos\delta \rangle d_\perp}{1 + \langle \sin\delta \rangle d_\parallel} \right|$$

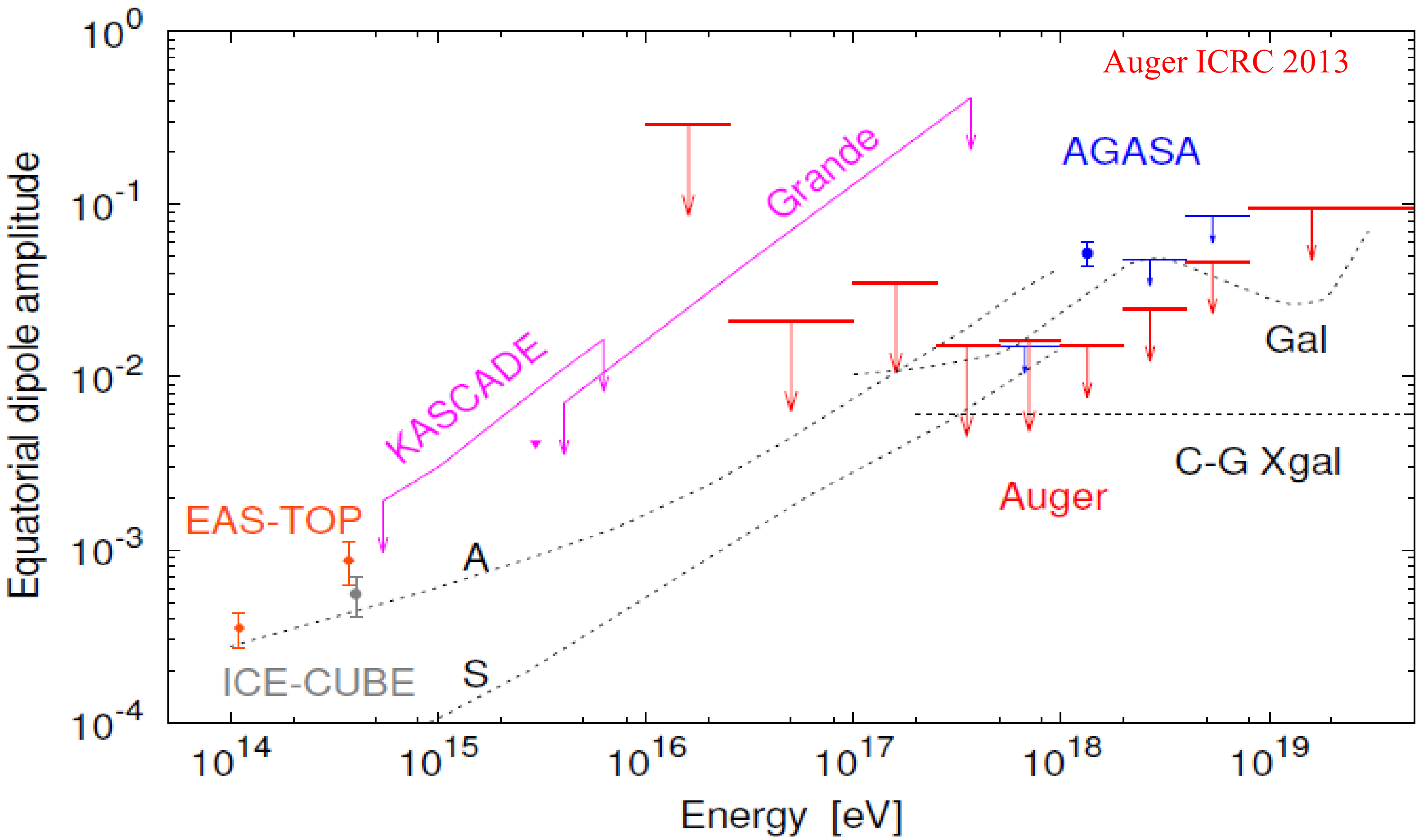
$$d_\perp \simeq r / \langle \cos\delta \rangle$$

Equatorial component allows comparison between different Observatories

3 bins above 1 EeV have isotropic probability < 1%

First-Harmonic analysis in Right Ascension

DIPOLE UPPER LIMITS



EeV energies: bounds are relevant to constrain models in which ankle is signature of galactic-extragalactic transition or in which a dominant galactic component extends to the highest energies

Highest energies: inhomogenous "local" LSS has dipole term that may manifest (with reduced amplitude and distorted by magnetic effects) even below trans-GZK energies

SEARCH FOR DIPOLE AND QUADRUPOLE PATTERNS

As a function of both right ascension and declination

First-Harmonic analyses in Right Ascension benefit from almost uniform exposure of ground-based and high duty-cycle Observatories

But are not sensitive to a dipole component along the Earth's rotation axis

Full multipole analysis:

$$\Phi(\mathbf{n}) = \sum_{\ell \geq 0} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{n}) \longrightarrow a_{\ell m} = \int_{4\pi} \mathrm{d}\Omega \; \Phi(\mathbf{n}) Y_{\ell m}(\mathbf{n})$$

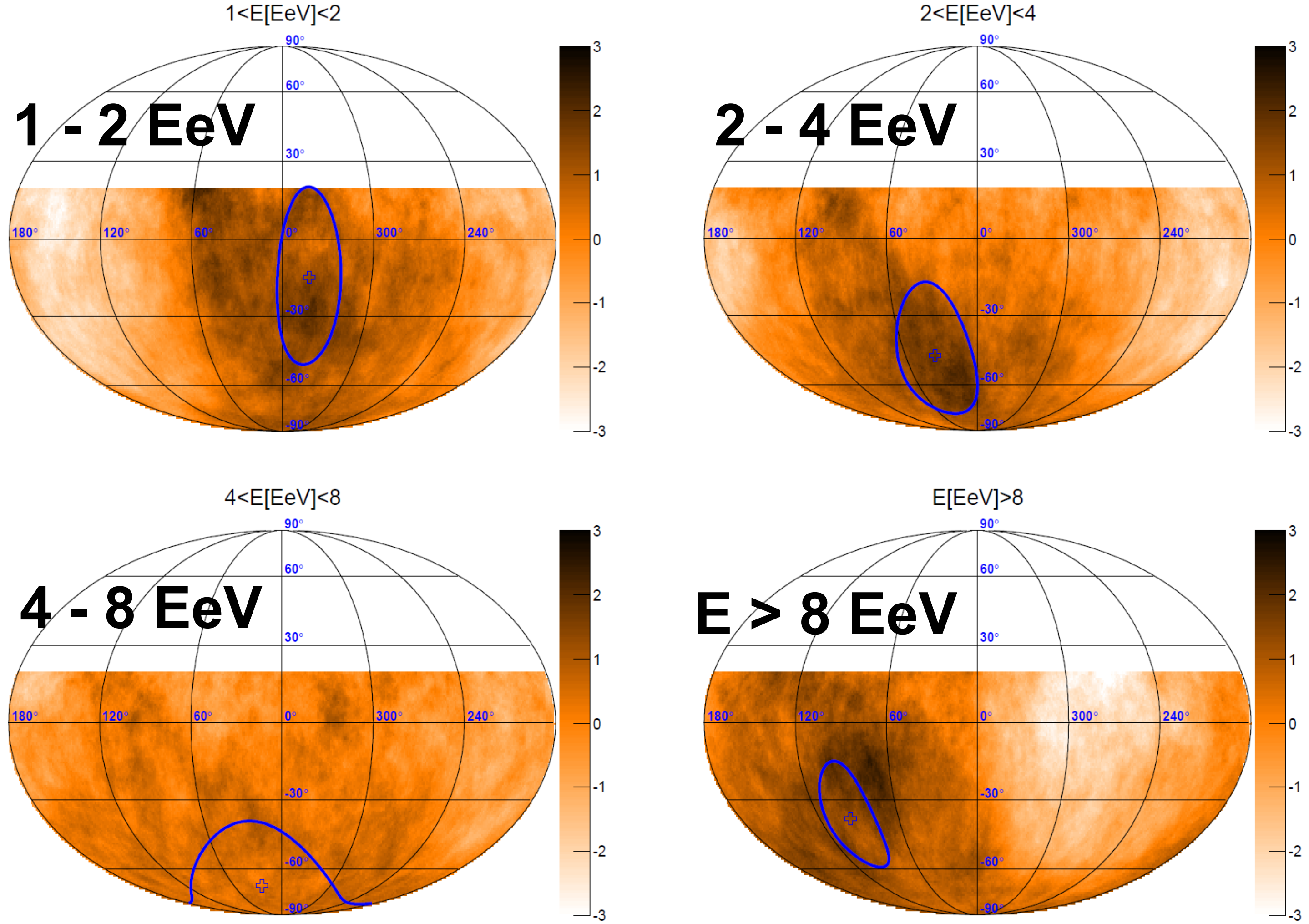
Incomplete sky-coverage and non-uniform exposure:

$$b_{\ell m} \; = \; \int_{\Delta\Omega} \mathrm{d}\Omega \; \omega(\mathbf{n}) \Phi(\mathbf{n}) Y_{\ell m}(\mathbf{n}) = \sum_{\ell' \geq 0} \sum_{m'=-\ell'}^{\ell'} a_{\ell' m'} \int_{\Delta\Omega} \mathrm{d}\Omega \; \omega(\mathbf{n}) Y_{\ell' m'}(\mathbf{n}) Y_{\ell m}(\mathbf{n})$$

$a_{\ell m}$ can be recovered without bias if

$\Phi(\mathbf{n})$ has no significant multipoles beyond $\ell_{\max}$

Sky-maps of significances (60º smoothing)
excess/deficit relative to isotropic expectations
and direction of fitted dipole



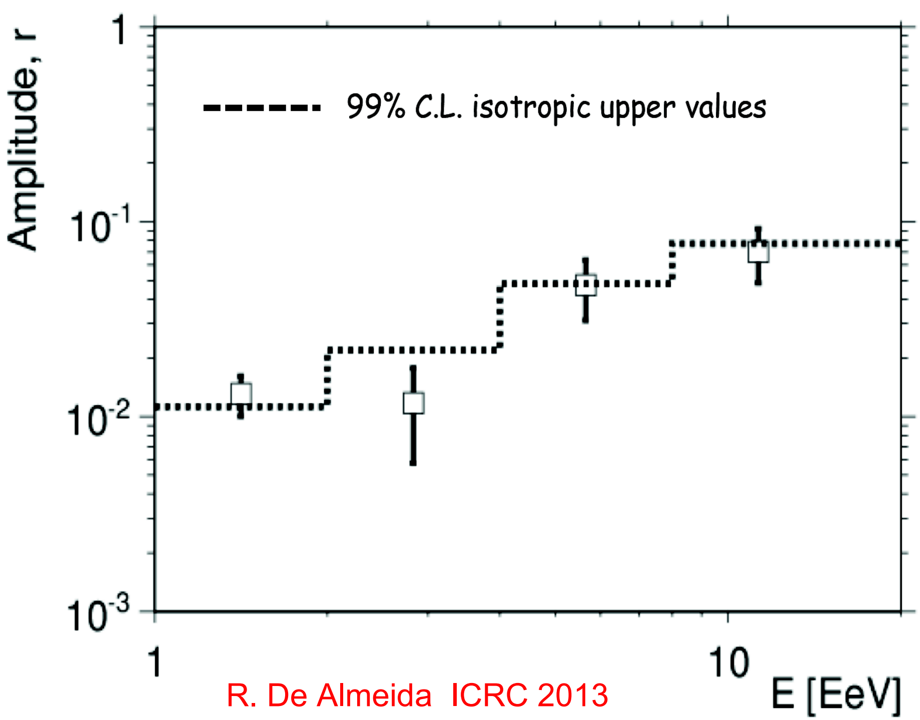
DATA: 1 January 2004 – 31 December 2011 **SD 1500 m array – Zenith < 55º**

ApJL and ApJS (2013)

DATA: 1 January 2004 – 31 December 2012

FIT TO A DIPOLE PATTERN

$$\Phi(\mathbf{n}) = \frac{\Phi_0}{4\pi}\left(1 + r\,\mathbf{d}\cdot\mathbf{n}\right)$$



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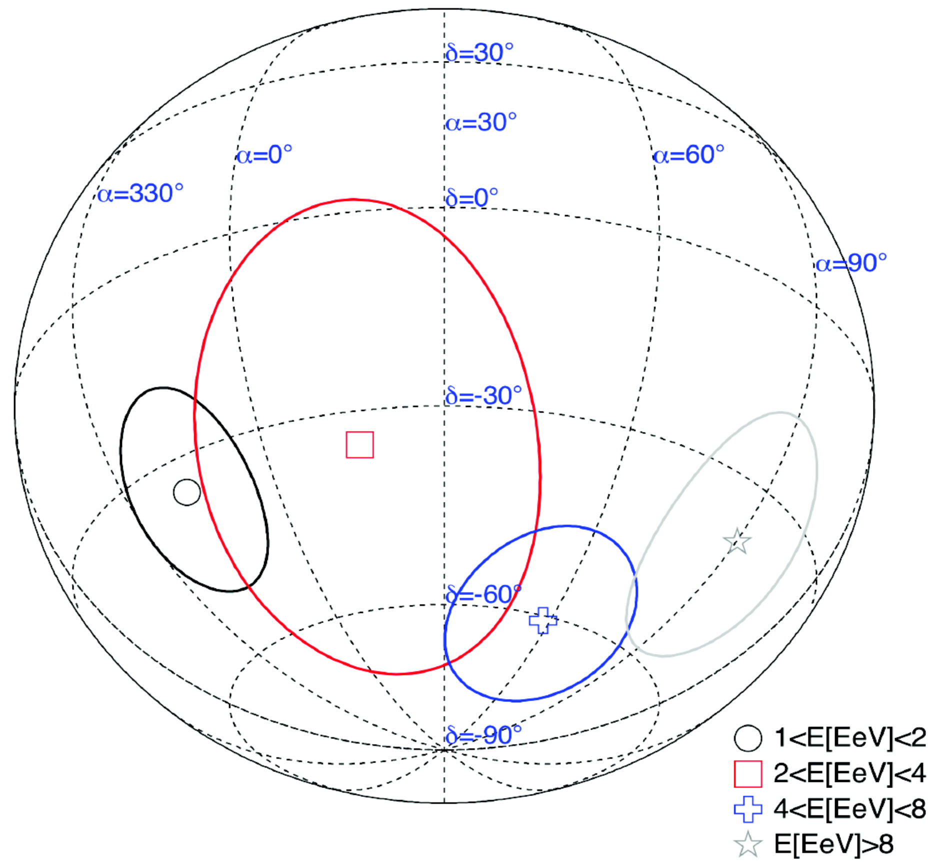


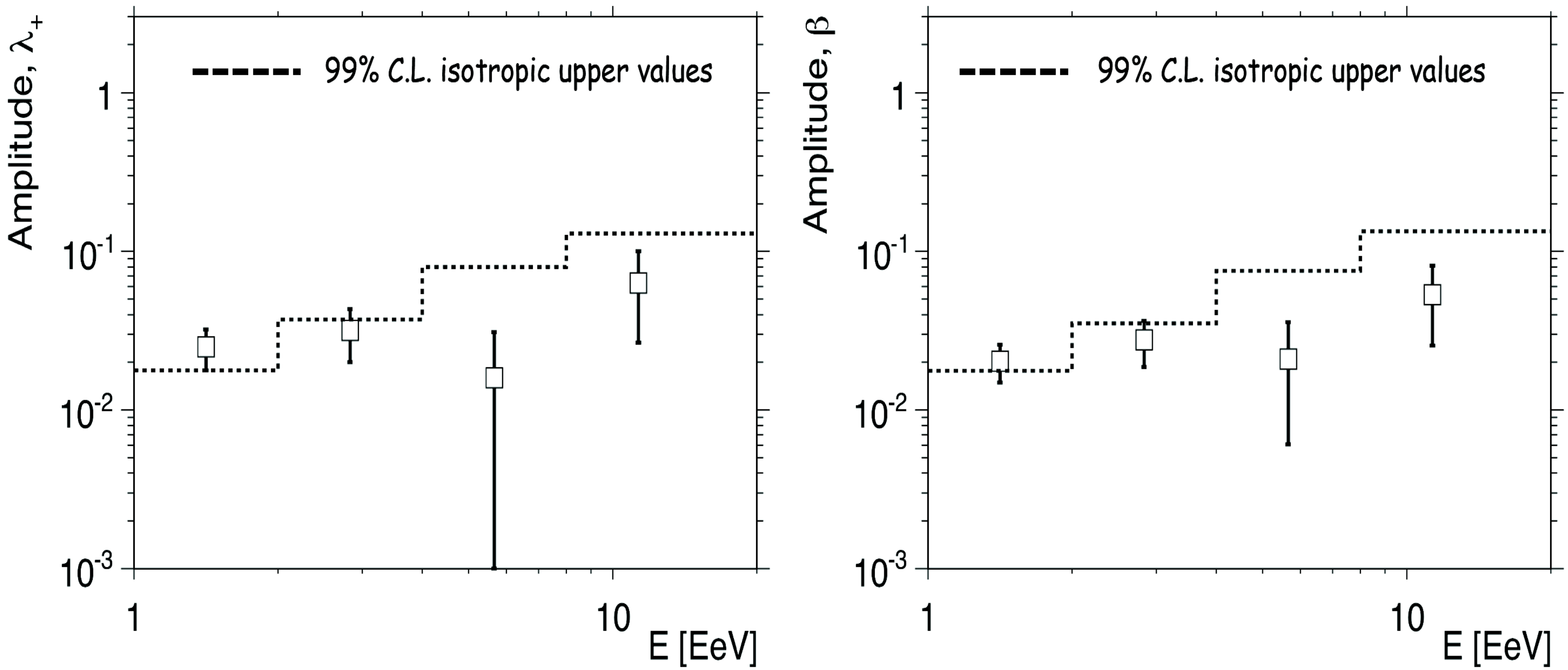
Hints of a dipole

Consistent with results of first-harmonic measurements in Right-Ascension only

FIT TO DIPOLE + QUADRUPOLE

$$\Phi(\mathbf{n}) = \frac{\Phi_0}{4\pi}\left(1 + r\ \mathbf{d}\cdot\mathbf{n} + \lambda_+(\mathbf{q}_+\cdot\mathbf{n})^2 + \lambda_0(\mathbf{q_0}\cdot\mathbf{n})^2 + \lambda_-(\mathbf{q}_-\cdot\mathbf{n})^2\right)$$

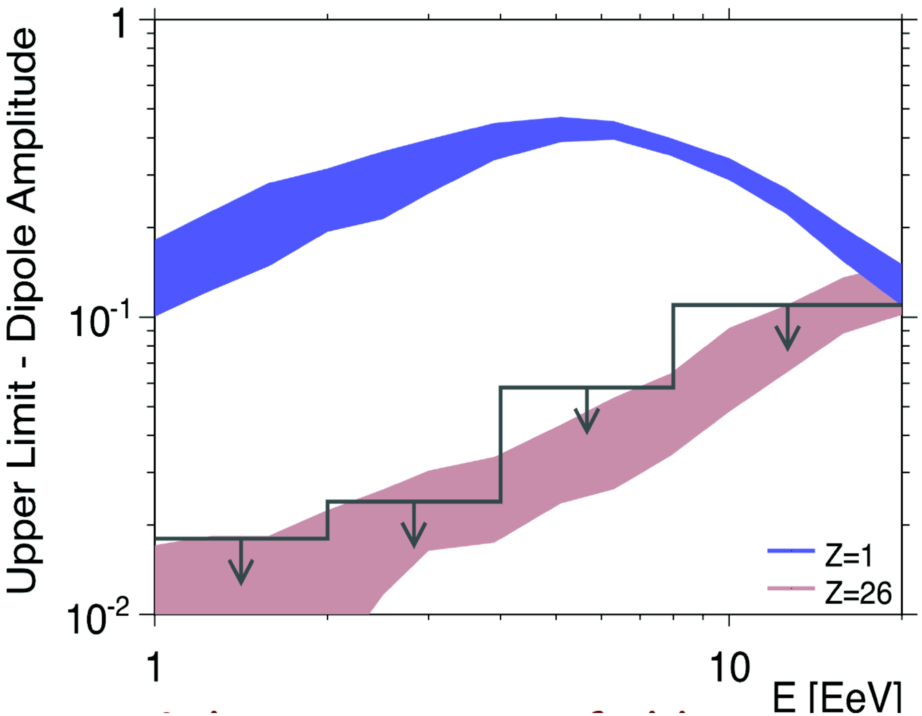
$$\beta \equiv \frac{\lambda_+ - \lambda_-}{2 + \lambda_+ + \lambda_-}$$

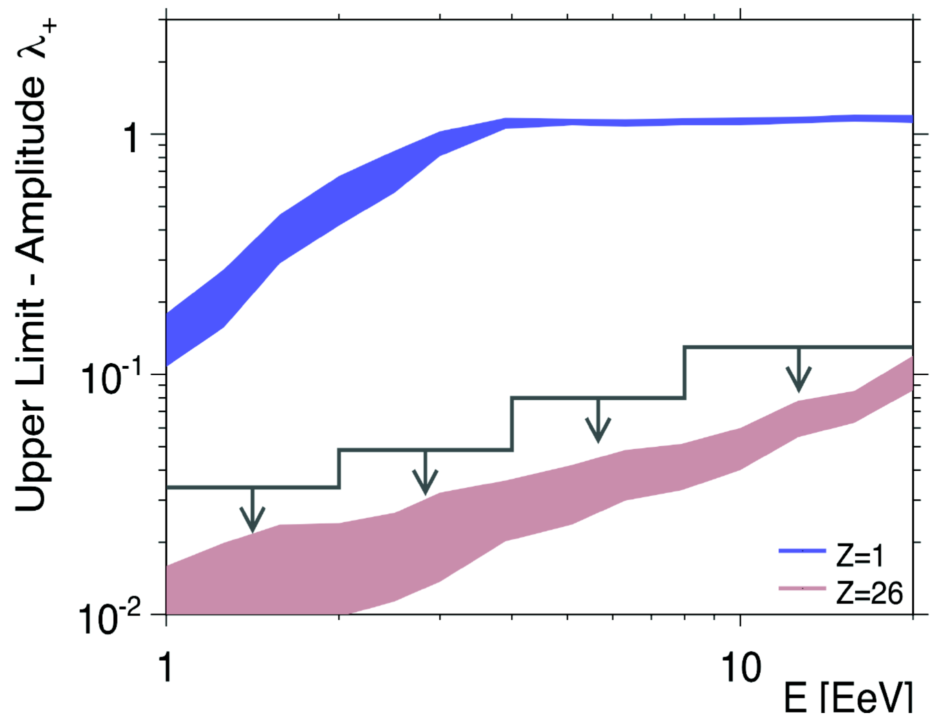


Hints of a quadrupole moment at EeV energies

UPPER LIMITS (99%CL)

Constrain galactic origin of light component





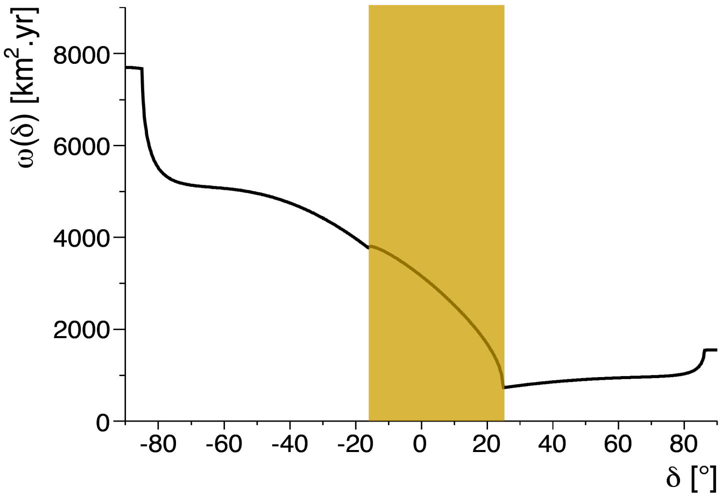
MODEL: stationary, uniformly distributed isotropic sources in the galactic disk

regular disk (BSS) and halo (A) galactic field + Kolmogorov turbulent component

FULL-SKY SEARCH ABOVE 10 EeV (Joint Auger – TA project, ongoing)

UNAMBIGOUS measurement of multipoles requires full-sky coverage

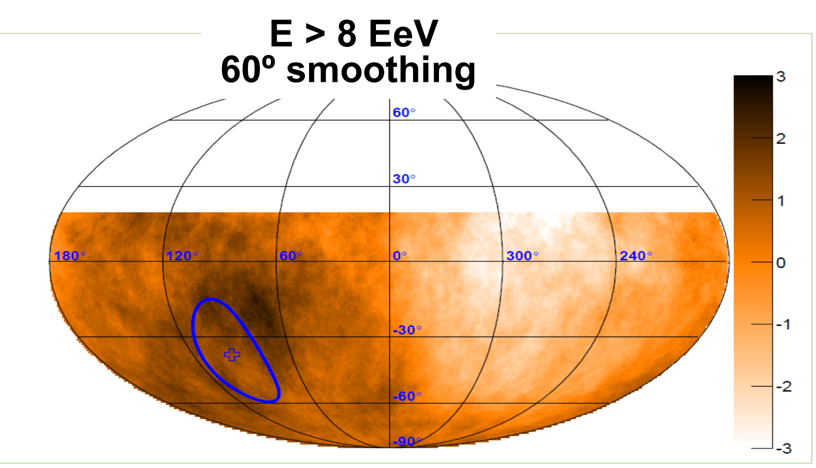
Ongoing joint Auger-TA project to combine data from two hemispheres and measure dipole above 10 EeV with full-sky coverage

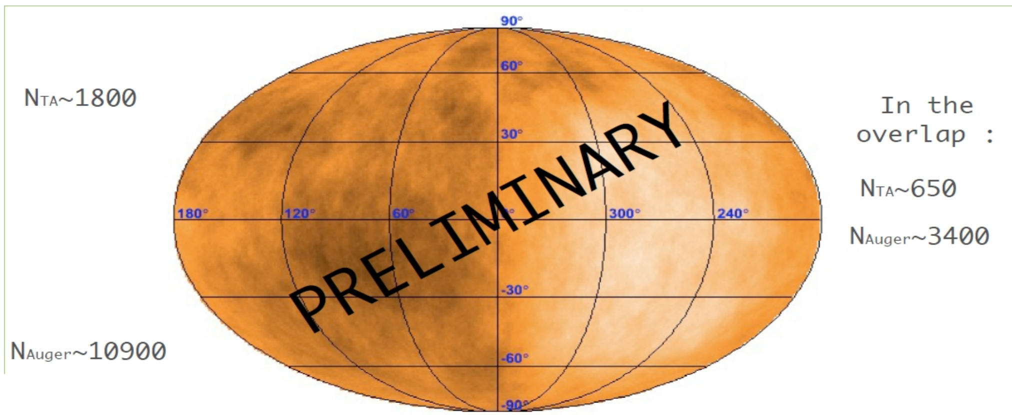


Results sensitive to relative exposures of the two experiments

$$\omega(\mathbf{n};b) = \omega_{\mathrm{TA}}(\mathbf{n}) + b\,\omega_{\mathrm{Auger}}(\mathbf{n})$$

Iterative process to determine "fudge factor" *b* that absorbs systematics (energy scale, etc.) through analysis of overlap region (declinations [-15º,25º])





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SUMMARY/OUTLOOK

UPDATED UPPER LIMITS ON DIPOLE AND QUADRUPOLE PATTERNS

Challenge to models with a galactic light component at EeV energies
(measurements suggest light composition around 1 EeV)

HINTS OF LARGE-SCALE ANISOTROPY

Constant phase of first-harmonic in right ascension in independent energy ranges points to ~ 270º (GC direction) below 1 EeV and ~ 90º at higher energies
Ongoing test with independent data

Dipole amplitudes with isotropic probability < 1% in some energy ranges
Must be scrutinized with further data

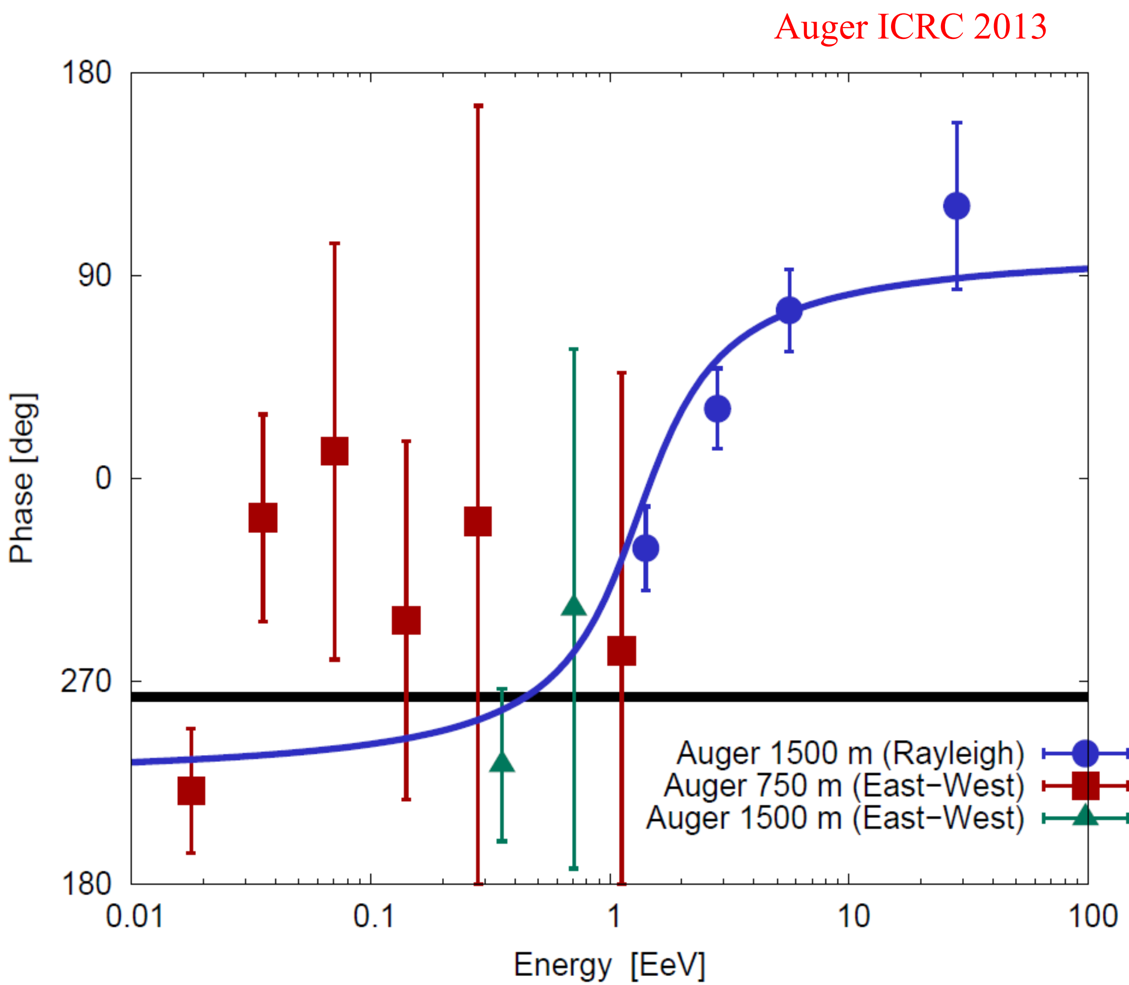
JOINT AUGER - TA FULL SKY ANALYSIS

In progress

First-Harmonic analysis in Right Ascension

DIPOLE PHASE

Midterm status of the test with independent data



Data from June 2011 until Dec. 2012

Still large uncertainties with curent data from 750m array

Overall good agreement with current data from 1500 m array